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# The formation of the Galactic bulge: clues from metal–rich globular clusters

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We compare the kinematics, spatial distribution, metallicities and ages of the globular clusters with the different components of the Milky Way: disk, bulge and halo. It is concluded that the metal–rich globular clusters with $R \leq 3$ kpc are associated with the Galactic bulge rather than the thick disk. We discuss the implications for the formation of the inner Milky Way.

## 1. Introduction

### 1.1. *The Galactic globular cluster system*

There are only ~150 globulars in the galaxy. This limits the statistics in studies of the globular cluster system.

Frenk & White (1980, 1982) analyzed a sample of about 60 clusters with high quality data at the time to study the kinematics and dynamics of the globular cluster system. They found the metal–rich clusters to be very concentrated towards the Galactic center: all clusters with [Fe/H] $\geq -0.8$ lie within the Solar circle. Indeed, looking at the spatial distribution, it is tempting to conclude that the metal–rich globulars are associated with the bulge.

Zinn (1985) found a bimodal metallicity distribution in a homogeneous sample of about 110 clusters, with peaks at [Fe/H] $\sim -1.5$ and $-0.5$. From the spatial distribution and kinematics, he concluded that the metal–rich clusters ([Fe/H] $\geq -0.8$) form a disk system, with the rest belonging to a halo system. This division between halo and disk was supported by Armandroff (1989), who associated the disk clusters with the thick disk. No clusters were associated with the bulge at that time, because the bulge was thought to be very metal–rich (mean [Fe/H] $= +0.3$, after Rich 1988), and with a very large velocity dispersion ($\sigma = 113$ km/s, after Mould 1983). Also, very few clusters within 2 kpc of the Galactic center had been studied.

### 1.2. *The Galactic bulge*

In the last few years, our ideas about the bulge structure, kinematics and metallicity have changed. In particular, McWilliam & Rich (1994) revised the mean metallicity of the bulge downwards by 0.55 dex. The mean metallicity of Baade's window (at $R = 0.5$ kpc) is now [Fe/H] $= -0.25$. Minniti (1994) have obtained spectra for about 700 bulge giants in three different windows, deriving accurate radial velocities and metallicities. The lower abundance scale is confirmed by these data: we find a mean [Fe/H] $= -0.5$ at $R = 1.5$ kpc. Also, Minniti (1994) finds that the bulge velocity dispersion drops from $\sigma \approx 110$ km/s at $R = 0.5$ kpc to $\sigma \approx 60$ km/s at $R = 2.0$ kpc, and that the bulge is consistent with an oblate isotropic rotator with rotation velocity $V \approx 110$ km/s. In the light of these new data, we can re–examine the comparison in kinematics, spatial distribution, ages and metallicity of the bulge and disk with that of the metal–rich globulars.



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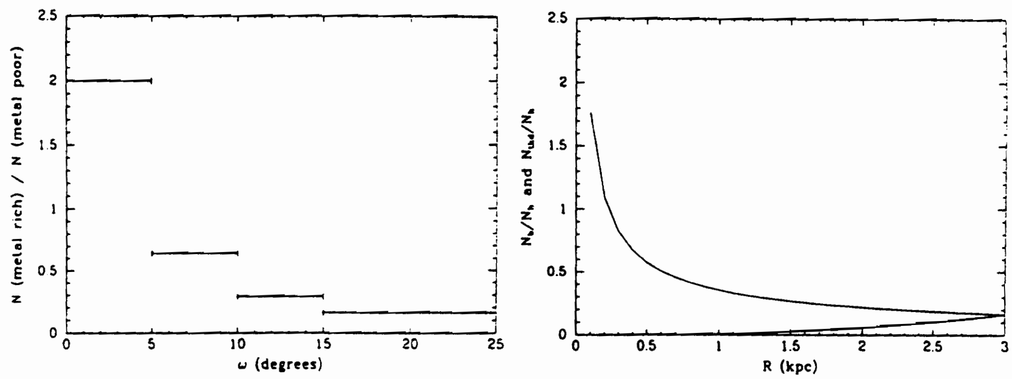


FIGURE 1. (*a*) Observed relative numbers of metal–rich to metal–poor clusters *vs* Galactocentric distance; *b*) Expected relative numbers predicted by our simple Galactic model. The upper and lower curves represent $N_{bulge}/N_{halo}$, and $N_{thick\ disk}/N_{halo}$, respectively.

## 2. Evidence for a bulge population of metal–rich globulars

### 2.1. *Spatial distribution*

When looking at the spatial distribution of metal–rich globulars and the bulge, a direct comparison of the scale–lengths and scale–heights is not constructive, since clusters were preferentially destroyed in the inner galaxy (Aguilar et al. 1988). Instead, what one can do is to compare the relative numbers of metal–rich to metal–poor clusters as function of distance. This is plotted in Figure 1a, using data of Zinn (1990). The ratio $N_{metal\ rich}/N_{metal\ poor}$ increases steeply towards the Galactic center, as expected if the metal–rich clusters follow the bulge rather than the thick disk. Let us check this by looking at a very simple Galactic model, with the following densitie laws:

- Halo: $\rho_h \sim r^{-n}$, with $n = 3.0 - 3.5$, from halo globulars, RR Lyraes and field BHB stars (Zinn 1985, Saha 1985, Preston et al. 1991).
- Bulge: $\rho_b \sim r^{-m}$, with $m = 3.65 - 4.2$ from K and M giants, IRAS sources, and the integrated K light (Terndrup 1988, Frogel 1988).
- Thick disk: $\rho \sim e^{-h_r/r} e^{-hz/Z}$, with $h_r = 3.5$ kpc, $h_Z = 1.0$ kpc, from star counts (Ojha et al. 1994).

The results of the expected $N_{bulge}/N_{halo}$ and $N_{thick\ disk}/N_{halo}$ are shown in Figure 1b, normalized to $N_i/N_{halo} = 0.16$ at $R = 3$ kpc. Since the relative increase of the halo power law is always faster than an exponential law towards $R = 0$, the thick disk underpredicts the number of globulars in the inner 3 kpc, and overpredicts the number of outer globulars. On the other hand, the functional form of the ratio agrees with the hypothesis of the clusters belonging to the bulge.

### 2.2. *Kinematics*

Armandroff (1989) measured the rotation and velocity dispersion for metal–rich globulars to be $V_{rot} = 177 \pm 25$ and $\sigma = 58 \pm 11$, which are different than the bulge values (Section 1). The metal–rich globulars seem to rotate faster than the bulge, but this rotation signal is dominated by the clusters *outside* of 3 kpc. Furthermore, Armandroff (1989) followed the constant rotation solution method developed by Frenk & White (1980), which may

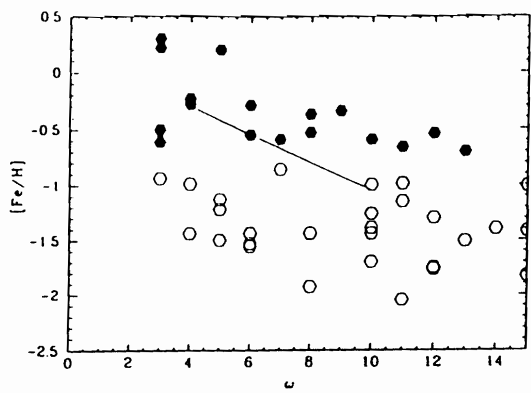


FIGURE 2. (*a*) Globular cluster metallicity *vs* angular distance from the Galactic center; (*b*) Globular cluster metallicity *vs* Galactic latitude. Filled circles indicate clusters with [Fe/H] $\geq -0.8$. The mean bulge metallicity is plotted as a solid line from the data of Terndrup (1988), rescaled according to McWilliam & Rich (1994).

not apply to the bulge: the available data are more consistent with the model of Kent (1992).

Fortunately, the line of sight velocity dispersion of the disk globulars is not affected by the rotation solution. It is then legitimate to compare directly the velocity dispersions of the different systems. For the metal rich systems with $\omega \leq 15$ degrees (R $\leq 2.1$ kpc):

* Metal–rich globulars: $\sigma = 77 \pm 14$ km/s
* Metal–rich bulge giants: $\sigma = 72 \pm 4$ km/s at 1.5 kpc

These velocity dispersions are indistinguishable. Also, the inner metal poor systems give:

* Metal–poor globulars: $\sigma = 126 \pm 20$ km/s,
* Metal–poor halo giants: $\sigma = 109 \pm 13$ km/s at 1.5 kpc

These values suggest that the metal–poor stars and clusters in the inner few kiloparsecs are just the natural inner extension of the halo. Note that the velocity dispersion of the old disk increases towards the Galactic center (Lewis & Freeman 1990). Then, the inner disk velocity dispersion is expected to be much larger than the observed numbers:

* Old disk within 3 kpc: $\sigma \sim 100$ km/s

which would seem to rule out the disk as host of the metal–rich globular cluster system.

### 2.3. *Metal abundances*

The mean metal abundance of the inner (R $\leq$ 3 kpc) metal–rich globular clusters is [Fe/H] $= -0.49 \pm 0.05$ (Armandroff 1989). With the new metallicity scale for the bulge, based on the abundances derived by McWilliam & Rich (1994) and by us, there is no appreciable difference between the mean abundances of the bulge and metal–rich globulars. This is illustrated in Figure 2, which shows the bulge and cluster metallicities as function of angular distance from the Galactic center and as function of Galactic latitude.

### 2.4. *Ages*

Star clusters are excellent probes of the ages of different stellar populations, since they have very well defined sequences in the color–magnitude diagrams. This is because all member stars are coeval and have similar chemical composition. However, it is very difficult to measure ages of the inner metal–rich globulars, due to heavy reddening, and to foreground contamination by the disk and bulge. Nevertheless, several studies indicate that these clusters are younger than the halo globulars, with ages $\sim 10 - 13$ Gyr (e.g. Hodder et al. 1993, Demarque & Lee 1992, Fullton 1994 –this volume–).

It is even more difficult to obtain the mean age of the Galactic bulge, because of the same problems, added to the finite depth along the line of sight and to the wide metallicity range. However, most recent studies seem to converge towards a mean age of $\sim 10$ Gyr for the bulge (Terndrup 1988, Holtzmann et al. 1993), although it is not clear if there is an age range. Even though we cannot be sure that the bulge and the metal–rich clusters have the same age, it is clear that the current determinations are consistent.

## 3. Discussion

It seems clear that the metal–rich globular clusters with $R \leq 3$ kpc are associated with the Galactic bulge rather than with the thick disk.

An important implication is that the bulge must be younger than the halo. This is in direct contradiction with the picture of Galaxy formation presented by Lee (1992), who proposed that the bulge is 1.5 Gyr older than the halo, based on RR Lyraes in Baade's window. We argue that the RR Lyraes, like the metal–poor globulars, represent the inner extension of the halo and do not tell us anything about the mean age of the bulge.

### 3.1. *How did the bulge form?*

An exhaustive discusion of different scenarios of bulge formation can be found in Wyse & Gilmore (1992). We can now speculate about the origin of the bulge, using the argument that the metal–rich globulars belong to this component, trying to complement the discussion of Wyse & Gilmore (1992):

• Large merging event or strong interaction?

As argued by Ashman & Sepf (1992) among others, multiple peaks in the metallicity distribution of globular clusters may be the result of a late merging event. Such violent episodes can lead to the formation of globulars in the inner regions of a galaxy. Since the metallicity distribution of globulars is bimodal in the Milky Way, it is worth exploring further this possibility.

• Strong bar instability heating up the inner disk?

Pfenniger & Norman (1990) suggested that a strong bar potential in the inner disk could create a concentration of stars in the center, which then are heated out of the Galactic plane by resonances. It would be worth to check if such a scenario will produce metallicity gradients such as observed in the bulge, and if it would affect in the same way the orbits of the globulars associated with the bulge.

• From the gas clouds ejected by a violent starburst?

Sofue & Habe (1992) suggested such a scenario to explain the formation of bulges and the origin of Hubble morphological types. It would be interesting to check if such a process can form metal–rich globular clusters.

• Dissipational collapse, using leftover gas from the formation of the halo?

Carney et al. (1990) pointed out that most of the gas leftover from halo formation would have sinked towards the bulge, due to its low angular momentum. Thus, the picture of Eggen et al. (1962), where the protogalactic cloud contracts at the same time that is forming stars, seems very atractive. Such scenario will reproduce the observed metallicity gradient naturally. The metal–rich clusters will also be more concentrated than the metal–poor clusters, as observed. The strong dependence of kinematics on metallicity (Minniti 1994) also seem to support this scenario.

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## Questions

**B. Carney:** One of the key questions is whether the formation and evolution of the bulge is related to the disk, the halo or is independent. Rosie Wyse and Gerry Gilmore proposed a nice test: the mass *vs* angular momentum distributions. Your data are an excellent contribution to that problem. Do you have any results yet?
**D. Minniti:** I do not have any definitive results yet on this test. However, the idea of a causal relationship between the formation of the halo and the bulge looks very atractive, since the gas lost from the halo formation would sink to the bulge due to its low angular momentum (Carney et al. 1990).

**J. Kaluzny:** Could you comment on the age of giants forming your sample?
**D. Minniti:** I have not determined ages directly for the giants of my sample. Other recent results seem to give a mean age for the bulge of $t \approx 10$ Gyr.